

N95-15147

24354

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**CENTRIFUGES IN GRAVITATIONAL
PHYSIOLOGY RESEARCH**Rodney W. Ballard, Phil Davies
and Charles A. Fuller*NASA Ames Research Center
Moffett Field, CA 94035-1000 USA
and*Section of Animal Physiology
University of California
Davis, CA 95616-8519 USA**INTRODUCTION**

Data from spaceflight and ground based experiments have clearly demonstrated the importance of Earth gravity for normal physiological function in man and animals. Gravitational Physiology is concerned with the role and influence of gravity on physiological systems. Research in this field examines how we perceive and respond to gravity and the mechanisms underlying these responses. Inherent in our search for answers to these questions is the ability to alter gravity, which is not physically possible without leaving Earth.

However, useful experimental paradigms have been to modify the perceived force of gravity by changing either the orientation of subjects to the gravity vector (i.e., postural changes), or by applying inertial forces to augment the magnitude of the gravity vector. The later technique has commonly been used by applying centripetal force via centrifugation [1].

The first recorded use of a centrifuge for gravitational research was by Knight (1808) who examined the effects of centrifugal force on plant growth patterns. Later in the 19th century Salathe' (1877) examined the effects of centrifugation on circulation and Tsiolkovsky (1878) explored G-tolerance. It wasn't until the work of Matthew's (1953), however, that chronic centrifugation was used to examine physiological adaptation to altered force loading. Since that time, several investigators have used chronic centrifugation to study a variety of species. These studies examined the effects of such a hyperdynamic environment on organism growth, development, physiological adaptation, and genetic selection, to name but a few.

The use of centrifuges in space was pioneered by the Russians, who flew a 75 cm diameter centrifuge on COSMOS 782 (1975) and 936 (1977). The results of these studies demonstrated the feasibility of such a facility in space. More recently, the US space program has utilized centrifuges in spaceflight on the German D-1 mission (1985), on SLS-1 (1991), on the plant growth facility and cell cultures on the ESA Biorack on IML-1 (1992), and most recently, the Frog Embryo Unit flown on Spacelab J (1992).

INERTIAL FORCE

Chronic acceleration via centrifugation results in the summing of inertial force due to rotation with the force of Earth gravity, causing an increase in the ambient acceleration force to which a subject is exposed (hyperdynamic field). As such, the forces produced on the surface of the Earth are never less than one G (1 G \equiv Earth gravitational force). However, centrifuges used in an orbiting spacecraft, where the ambient acceleration environment approximates $10^{-6}g$, can effectively produce an inertial field of any magnitude larger than 0 G.

There is a reciprocal relationship between radius and rotation rate which allows the same field to be developed at infinite combinations of radius and rotation rate. The basic physical relationships of a centrifuge are [1]:

$$a = r\omega^2; \text{ or}$$

$$G = a/g = r\omega^2/g$$

where:

- a** is the acceleration (inertial) force;
- r** is the radius of rotation;
- ω is the rotation rate (radians/time);
- G** is the field characteristic (the weight-to-mass ratio); and
- g** is the Earth's gravitational constant.

CENTRIFUGE/GRAVITY COMPARISONS

Gravity, a fundamental property of matter, is an attractive force existing between masses. Gravity produces motion when acting on unrestrained masses. Alternatively, when restrained from motion, gravitational forces produce the phenomenon of weight. Inertial force, on the other hand, is produced when the velocity of an object is changed, accelerated or decelerated. In theory, Einstein's "Principle of Equivalence" postulates that the forces produced by gravity and inertia should be indistinguishable [4].

However, in addition to providing an inertial force, centrifuges have technical and physical limitations which may, if not understood or controlled, obscure the gravitational effects [2]. Centrifuge geometry produces several distinct properties between gravity and inertial force, all of which are inversely related to the size of the radius of rotation. These potentially adverse aspects of centrifugation have not been critically examined. When centrifuge radii must be limited, such as in spacecraft, the rotational effects may interfere with research objectives. As such the effect of rotation must be considered during design of such centrifuges and as a factor in their experimental usage. Conversely, if the size of the centrifuge is severely constricted, the effect of that parameter must be fully understood and experiments designed with those limitations taken into consideration.

For example, G-gradients are inherent in all gravitational fields. In humans on Earth there is a calculable head-to-foot G-gradient. Thus, the problem of G-gradients in subjects on a centrifuge is a quantitative, rather than a qualitative, one. In practice, the possibility of such a biological influence has been recognized, and minimized, by utilizing centrifuges with a large radius (usually 2-3 m). However, in a spacecraft, centrifuge

radius is limited and any possible separate rotational influence from the effects of gravity must be identified.

Recent work has shown an effect of centrifuge diameter on the rate of adaptation of the feeding and drinking rhythms of squirrel monkeys (unpublished observations). Another affected variable was the amplitude of the body temperature rhythm. All variables recovered towards baseline more rapidly on a larger diameter centrifuge than they did on a smaller diameter centrifuge, both of which produced the same acceleration field. It is crucial that any interaction between rotation rate and G-field be thoroughly explored; such information may indicate the maximum fields (for a given radius) that do not develop interference from rotation effects.

Additional factors, such as coriolis and cross-coupled accelerations become an issue for mobile specimens. Movement induced acceleration of a subject on a rotating centrifuge will produce these additional forces. Coriolis forces are produced by movement along the radius or parallel to the direction of rotation. The force produced is perpendicular to the direction of movement. Cross-coupled accelerations are a result of rotation within the rotating environment. Again, the larger the diameter the facility, the smaller the relative contribution of these forces to any biological responses.

Finally, gravity gradients must also be considered. These gradients are proportional to the height of the subject relative to the radius of the centrifuge. While measurable on the Earth's surface, such gradients are considered to be inconsequential, however, they become significant on a centrifuge. Yet, little is known of the physiological significance of such gradients across an organism.

CENTRIFUGES IN SPACE

Spacecraft based centrifuges offer several advantages to the science community interested in gravitational physiology [3]. First, a centrifuge housing a group of experimental subjects in a force environment of 1 G provides an important control population for the responses of a parallel 0 G population. Since spacecraft provide several stimuli other than altered gravity (i.e., radiation, artificial atmosphere, etc.), responses measured in the 0 G population may not be solely due to the 0 G environment. In theory, however, if the responses of ground and flight 1 G populations are the same, this would imply that the responses of a 0 G population are solely due to the change in the gravitational field.

Second, the ability to produce field strengths between 0 and 1 G allow for the study of G threshold responses of subjects from various physiological systems. Current evidence suggests that some physiological responses may be detectable at any G greater than 0 G. Alternatively, some physiological systems may take a substantial increase in G before responses are initiated.

Third, animals adapted to 1 G in space can be exposed to an altered gravitational environment, such as 0 G, without the imposition of additional forces such as are encountered with the launch of a spacecraft. Further, subjects could be adapted to field intensities equivalent to other planets, such as the Moon (0.17G) or Mars (0.38G).

Fourth, the development of an artificial gravity countermeasure to long duration spaceflight will likely entail rotation of part or all of a spacecraft. An inflight centrifuge provides the opportunity to develop the requirements (i.e., intensity, duration, frequency, etc.) for such a countermeasure.

In general, these advantages are subsets of a potential principle of continuity. Although life on Earth has evolved at 1 G, it is reasonable to expect that physiological responses to gravity will vary as a function of the intensity of the gravity stimulus. A facility in space can produce G levels ranging from 0 G to any desired level. Thus, a continuum of responses are to be expected starting with a threshold stimulus and varying with some functional relation to G. This relationship may not be simple, nor even linear, over a range of G levels. In fact, it is reasonable to expect that some systems will be optimized for 1 G and will show a decrement in function at either higher or lower G levels.

Such a facility is currently being planned by NASA for use on Space Station Freedom. The facility is being designed to meet the needs for a variety of users. Specimens will include plants and small rodents. Later planning calls for the use of larger plants and non-human primates. Disciplines involved in the planning include: Cell and Developmental Biology, Plant Biology, Regulatory Physiology, Musculoskeletal Physiology, Behavior and Performance, Neuroscience, Cardiopulmonary Physiology, and Environmental Health and Radiation.

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